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PERFORMANCE AND DESIGN OF INTUMESCENT COATINGS ON CONCRETE FILLED HOLLOW STEEL SECTIONS

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ABSTRACT: Concrete filled hollow sections (CFS) are increasingly used in the design and construction of multi-storey buildings and can, in some cases, provide adequate fire resistance without the need for applied fire protection. When calculations show that unprotected sections have inadequate fire resistance, the CFS sections require protection and in many jurisdictions this usually takes the form of an intumescent coating. In practice the design of intumescent fire protection applied to CFS sections is typically based on three input parameters: (1) the required fire resistance (FR); (2) an effective section factor (H_p/A); and (3) an assumed limiting temperature of the steel. Current design guidance suggest using an ‘effective’ section factor these types of columns, which effectively replaces the contribution of the concrete core with an equivalent steel wall thickness, that has been shown to be overly conservative when used with intumescent coatings; temperatures observed during furnace tests are typically less than half the designed critical temperature at the as-designed presumed fire resistance time. A new design model and approach that calculates the instantaneous effective section factor for unprotected CFS columns was used to calculate effective section factors for four protected CFS columns, which were then fire tested in a furnace. The design effective section factors were less than the minimum tabulated values available from intumescent paint manufacturers, and so the minimum available section factor (25m^{-1}) was used to specify the intumescent thicknesses applied. The fire tests demonstrated that the new approach remains conservative and considerably simplifies the design of intumescent coatings on CFS sections – implying a single effective section factor for the vast majority of design situations.

KEYWORDS: Composite columns, intumescent fire protection, forensic analysis, section factor, design.

INTRODUCTION

Architects and engineers increasingly specify concrete filled steel hollow structural sections (CFS) in the design and construction of multi-storey buildings, since these are an attractive, efficient, and sustainable means by which to design and construct compressive members in highly optimized structural frames. A CFS section consists of a hollow steel section that is in-filled with concrete to provide, through composite action, superior load carrying capacity and structural fire resistance as compared with either an unfilled steel tube or a plain reinforced concrete section. The concrete infill and the steel tube work together, at both ambient temperatures and during fire, yielding several benefits: the steel tube acts as stay-in-place formwork during casting of the concrete, thus reducing forming and stripping costs, and provides a smooth, rugged, architectural surface finish; the concrete infill enhances the steel tube’s resistance to local buckling; and the steel tube sheds axial load to the concrete core (whether reinforced or unreinforced) when heated during a fire, thus enhancing the fire resistance of the column¹.

Multistorey buildings often require structural fire resistance ratings of two hours or more², which CFS sections can provide without the need for applied fire protection in some cases. However where the structural fire design guidance^{1,3-6} shows that adequate fire resistance is unachievable without protection, external fire protection must be applied to the steel tube; in the UK the preferred method of fire protection is by intumescent coatings.

In practice, the design of intumescent fire protection systems for CFS sections requires an assumed (typically prescribed) limiting steel temperature and a predefined (also prescribed) required period of standard fire exposure. Obtaining these is a difficult task for three reasons. Firstly, there is a paucity of test data on the performance of intumescent coatings when applied on CFS sections, due to the sensitive and unique composition of each specific intumescent coating product. Secondly, quantifiably observing the complex thermal response of intumescent coatings during fire resistance tests in furnaces is difficult. Intumescent fire protection coatings expand up to 100 times their original thickness⁷ when exposed to heat by creating a multi-cellular protective insulating layer, which is unique to the heating rate, chemical composition and the applied dry film thickness (DFT) of the coating. Lastly, fundamental differences exist between the evolutions of thermal gradients within protected, versus unprotected, CFS sections.

Previous work by the authors⁸ has assessed current fire resistant design guidance for intumescent fire protection systems applied to CFS sections in the UK, examining the prescription methods for DFTs on CFS sections and identifying the causes of overly conservative outcomes observed in a series of furnace tests on both protected and unprotected CFS columns. This prior work⁸ also proposed a new method for calculating the instantaneous effective section factor, a key variable within the design of the protective coating. The current paper assesses the new method and examines its potential design implications.

SPECIFICATION OF INTUMESCENT COATINGS FOR CFS SECTIONS

Design of intumescent fire protection (i.e. design DFTs) applied to structural steel is typically based on three input parameters: (1) the required *fire resistance*, F.R., which is typically from local building code requirements²; (2) a *section factor*, defined as the ratio of the section's heated perimeter, H_p , to its cross sectional area, A ; and (3) an assumed *limiting temperature* of the steel. Engineers use these three input parameters in conjunction with empirically determined, product specific, design tables to determine the required DFT of the specific intumescent coating needed to maintain the critical temperature of the steel below its critical temperature for the required duration of standard fire exposure. The product-specific design tables are based on numerous large scale furnace tests on plain structural steel sections with various H_p/A values and at a variety of applied DFTs.

To apply existing DFT tables for protection of CFS sections without the need to perform a large number of furnace tests, current design guidance suggests use of an 'effective' section factor, H_p/A_{eff} , which incorporates the effect(s) of the concrete infill on the heating rates of the steel and on the load bearing capacity of the composite column. Equations 1 and 2 give the current approach to determining the effective section factor for CFS sections⁹ used in the UK. Equations 1 and 2 treat the problem by using DFT design guidance developed for unfilled steel sections, but add an 'equivalent' steel wall thickness, t_{ce} , which is dependent on the internal breadth of the section, b_i , and the required fire resistance time, t_{FR} , to the existing steel wall thickness, t_s , to account for the thermal effects of the concrete core, thus decreasing the effective H_p/A :

$$\frac{H_p}{A_{eff}} = \frac{1000}{t_{se}} = \frac{1000}{t_s + t_{ce}} \quad (1)$$

$$t_{ce} = \begin{cases} 0.15b_i, & b_i < 12\sqrt{t_{FR}} \\ 1.8\sqrt{t_{FR}}, & b_i \geq 12\sqrt{t_{FR}} \end{cases} \quad (2)$$

This approach is physically unrealistic and thus limited (and potentially flawed) on a number of grounds. Neither the physical rationale nor the theoretical or empirical basis for Equation 2 are clear (or reported in the literature), however the best fit curve for the effective section factor was always conservative when compared against test data obtained by the authors (and others). Regardless, this is the current approach that is applied on real projects in the UK.

PREVIOUS ASSESSMENT OF CURRENT DESIGN APPROACH

The authors have previously assessed the performance of the current design method⁸ using equations 1 and 2 to prescribe the dry film thickness (DFT) for the fire protection of CFS sections. A summary of these findings is presented below.

Furnace Tests

Twelve protected and 12 identical but unprotected CFS sections were exposed to 120 minutes of ISO-834¹⁰ standard fire in a testing furnace. The intumescent coating DFT for the 12 protected CFS sections was prescribed using effective H_p/A values given by Equation 1, with a presumed limiting steel temperature of 520°C and a required F.R. of 90 minutes. Five different section sizes were assessed (120 × 120 mm □, 300 × 300 mm □, 139.7 mm Ø, 219.1 mm Ø and 323.9 mm Ø) with three different wall thicknesses, namely 5mm, 8mm, and 10mm. The effective section factors calculated using Equation 1 ranged from 40 m⁻¹ to 56 m⁻¹ for the 323.9 × 10 mm Ø and 120 × 120 × 5 mm □, respectively. The applied DFTs for the protected were all in the range of 3.45 to 3.60 mm. A schematic of typical test specimen layouts is given in Figure 1.

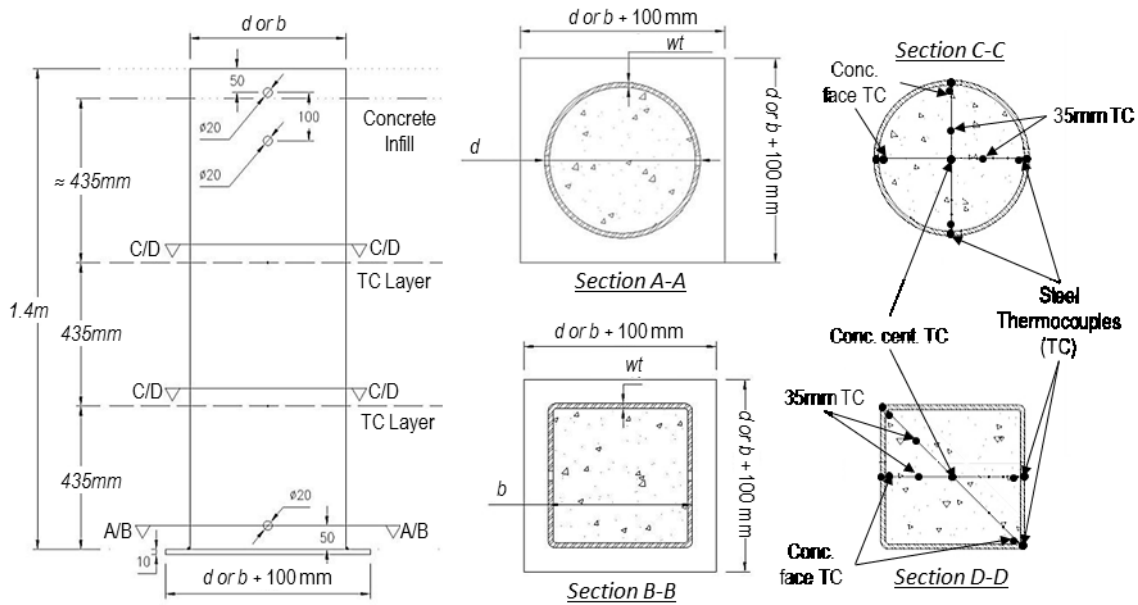


Figure 1: Specimen schematic layout.

Cross-sectional temperatures were recorded at two heights during testing, as shown in Figure 1, with eight K-Type thermocouples measuring steel tube, and 14 K-Type thermocouples measuring the thermal profiles within the concrete core. All specimens were constructed from Grade S355 structural steel sections and filled with a hybrid steel and polypropylene (PP) fibre reinforced concrete mix incorporating 40 kg/m³ and 2 kg/m³ of steel and PP fibres, respectively, with a compressive strength of between 46.1 and 59.4 MPa and a moisture content between 3% and 6% by mass at the time of testing. Full details of the tests, including residual (post-heating) structural tests to failure, are presented by Rush¹¹.

Results

Figure 2 shows a summary of the average, maximum, and minimum observed steel tube temperatures, θ_s , for all unprotected and protected tests. The results confirmed that the temperature difference between the steel tube and the centre of the concrete was much greater in unprotected sections than in those with protection. As expected, thermal gradients in protected CFS sections were much less severe, for the same steel tube temperature, than those in unprotected CFS sections. The data also

show that the observed steel temperatures in the protected sections were well below the target design limiting temperature of 520°C at the prescribed F.R. time. For instance, the maximum temperature experienced by any of the steel tubes protected to 90 minutes, at 90 minutes of exposure, was 264°C, more than 250°C less than the design limiting temperature of 520°C. The tests also demonstrated that the size of the concrete core affects the temperatures observed within the steel tube; with lower steel temperatures observed for CFS sections with proportionally larger concrete cores.

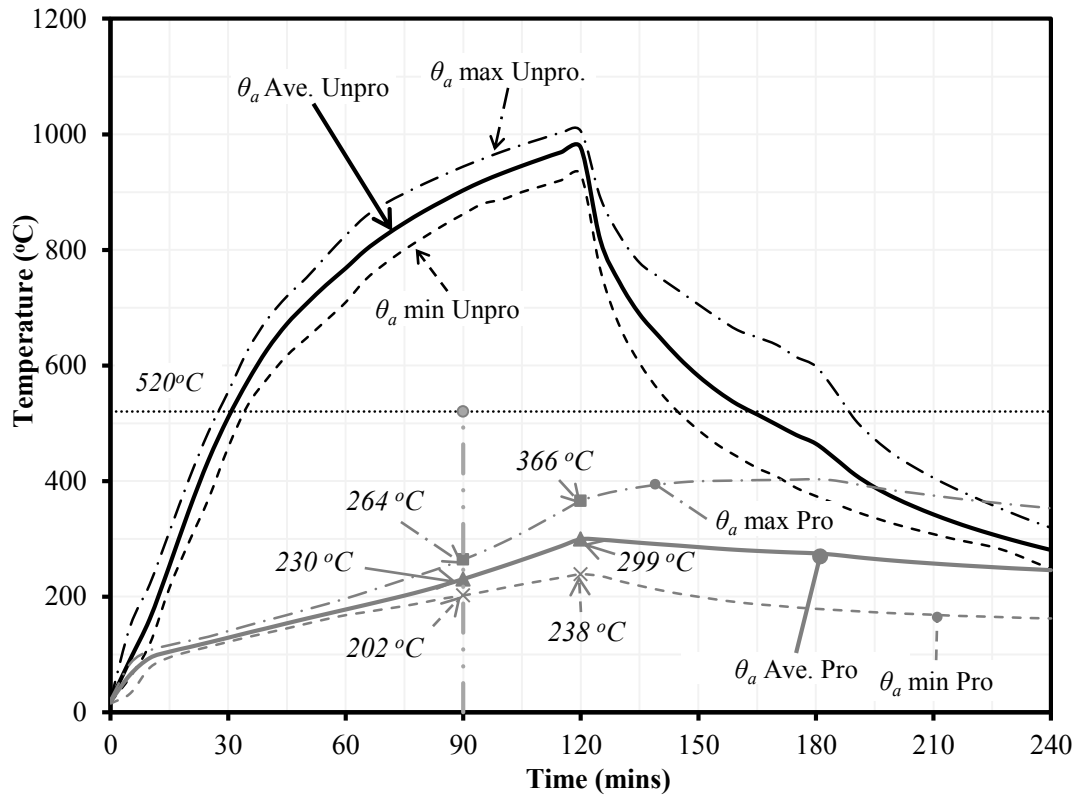


Figure 2: Comparison of unprotected and protected steel tube temperatures for CFS sections observed in furnace tests.

It is clear from the results presented previously by the authors⁸ that use of current guidance and DFT design data from unfilled steel sections to prescribe DFTs for CFS sections results in overly conservative steel tube temperatures during standard furnace testing; the limiting temperatures are never reached. Thus, if current guidance is used to prescribe DFTs for CFS sections excessive amounts of fire protection will be applied; while conservative this is clearly non optimal.

Discussion

The authors previously postulated three possible reasons for the observed conservatism in the test data: (1) inherently conservative DFTs in the tabulated data from unfilled section tests; (2) changes in the response, and thus the effective thermal conductivity, of the intumescent coatings when applied to sections with different thermal masses; or (3) incorrect or unrealistic calculation of H_p/A_{eff} for CFS sections.

Reason (1) was dismissed since available product specific tabulated DFTs are highly optimised for protecting plain steel sections, while Reason (2) was also dismissed through calculation of the effective variable thermal conductivity¹² of the intumescent char, showing no observable differences between unfilled and concrete filled hollow sections. Reason (3) was found to be the cause of the error, however not because of inaccuracies in the development of equations 1 and 2 but rather due to false assumptions being made during their development.

The existing effective section factor, H_p/A_{eff} , guidance given in Equations 1 and 2^{9,13} assumes that:

- 1) CFS sections can be treated as hollow steel tubes in which the concrete core provides an equivalent additional thickness of steel wall, using an empirical equation based on its required fire resistance time;
- 2) the effective section factor for unprotected CFS sections can be determined in the same manner as protected CFS sections, as is the case for protected versus unprotected unfilled sections; and
- 3) that the increase in steel temperature for an unprotected steel hollow section, or for a CFS section where the concrete is converted into an equivalent thickness of steel, can be calculated using a simple energy balance, for example from BS EN 1993-1-2¹⁴:

$$\Delta\theta_{s,t} = \frac{\dot{h}_{net}}{c_s \cdot \rho_s} \cdot \frac{H_p}{A} \cdot \Delta t \quad (3)$$

where the increase in steel temperatures, $\Delta\theta_{s,t}$, during a time interval, Δt , is determined based on the section factor, H_p/A , the net heat flux, \dot{h}_{net} ¹⁵, and the thermal capacity of the steel, $c_s \cdot \rho_s$.

Through a forensic analysis⁸, where the same process that led to the original guidance (equations 1 and 2) was followed using new data from 12 unprotected furnace tested CFS columns, the three assumptions above were assessed. It was shown that Assumption 2) was false. It was reasoned that the effective section factor of similar protected and unprotected CFS sections will be very different due to the fundamental differences in the thermal gradient within a protected CFS section compared to that within an unprotected section, with protected CFS sections experiencing a much less severe thermal gradient within the concrete infill which effectively increases the effect that the concrete core has on the effective section factor.

It was shown through the previously presented experiments⁸ that the thermal gradient within a protected CFS section is dependent upon the heating rate that the steel experiences, which in turn is affected by:

- the limiting temperature to which the steel is protected, since higher limiting temperatures result in more severe thermal gradients in the core and diminish the effect of the concrete;
- the required fire resistance period, with longer fire resistances producing shallower thermal gradients and increasing the effect of the concrete core; and
- the performance of the specific intumescent coating employed, particularly its variable effective thermal conductivity and physical charring characteristics, with increasing fire exposure.

To avoid conservatism and develop an improved design guidance, it was recognized that a broad range of analytical and experimental work would be required considering a wide variety of heating rates to the steel so that the effective section factors for protected CFS sections could be better understood so that a rational means of prescribing DFTs for protected CFS columns could be found. The authors⁸ concede that until a more fully rationalized approach is developed, the conservative guidance from equations 1 and 2⁹ should be used, however it is desirable to develop some interim guidance that reduces the major conservatism (i.e. inefficiencies) shown in Figure 2, and reduces the amount of intumescent coating required. Reductions in paint thickness not only reduce material costs but also the cost of application.

NEW INTERIM DESIGN METHOD

During the forensic analysis conducted by the authors⁸ a more realistic calculation model to determine the instantaneous effective section factor, H_p/A_{eff} , for unprotected CFS columns was proposed, as is given in Equation 4. The new calculation model converts the concrete core into an equivalent *area* of steel based on the size of the core, A_c , the ratio of the respective heat capacities of

concrete and steel ($c_c \cdot \rho_c$ and $c_s \cdot \rho_s$ for concrete and steel, respectively), and an empirically determined concrete core efficiency factor, η .

$$\left(\frac{H_p}{A_{eff}} \right)' = \frac{H_p}{A_s + \eta \cdot \frac{(c_c \cdot \rho_c)}{(c_s \cdot \rho_s)} \cdot A_c} \quad (4)$$

where $c_c = 1000 \text{ J/kg}^\circ\text{C}$, $\rho_c = 2300 \text{ kg/m}^3$, $c_s = 600 \text{ J/kg}^\circ\text{C}$, and $\rho_s = 7850 \text{ kg/m}^3$; these values are taken from BS EN 1994-1-2.¹⁶

The apparent concrete core efficiency factor, η , was found to vary with length of fire exposure. It was also found that the smaller cores had higher values of η as they have less thermal mass and thus heat up more rapidly. The relationship between the concrete core efficiency factor, η , the internal breadth of the section, b_i , and time of furnace exposure, t_{furn} , was determined through experiments to be an inverse function, since η must always remain positive and decrease as the core size increases. The calculation of η can thus be expressed, based on curve fitting from test results, in terms of the internal breadth, b_i , and time of furnace exposure, t_{furn} , as:

$$\eta = \begin{cases} 0.008023 \cdot b_i^{-0.527} \cdot t_{furn} & \text{Circular} \\ 0.003763 \cdot b_i^{-0.963} \cdot t_{furn} & \text{Square} \end{cases} \quad (5)$$

This more physically realistic calculation method (Equation 4) was found to accurately predict the observed effective section factors (calculated by re-arranging Equation 3⁸ for $H_p/A_{eff} (exp)$) of the unprotected CFS sections and, as shown in Figure 3 for time periods where CFS sections might require protection (30 mins and beyond), falls below the theoretical section factor calculated from current guidance (i.e. Equation 1 for $H_p/A_{eff} (Th)$).

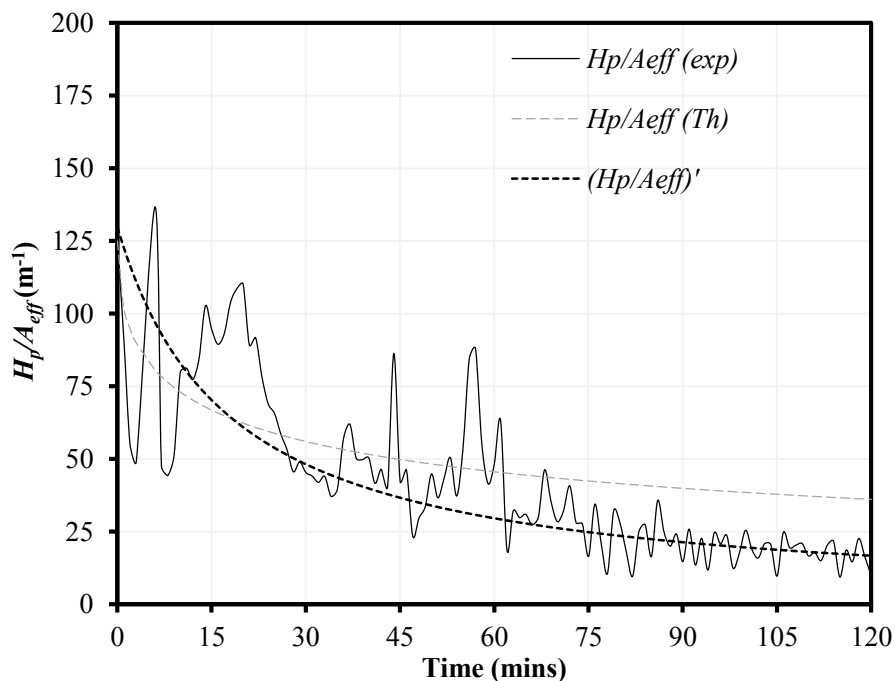


Figure 3: Comparison of $(H_p/A_{eff})'$, $H_p/A_{eff} (exp)$, and $H_p/A_{eff} (Th)$ values for a representative unprotected CFS section (in this case a $219.1 \text{ } \varnothing \times 8 \text{ mm}$ wall thickness circle).

The new instantaneous effective section factor calculation model for unprotected CFS sections could be conservatively used to prescribe the DFTs of intumescent coatings for protected CFS sections as

very different thermal profiles existing within unprotected and protected CFS section. Protected CFS sections will have a shallower thermal profile than that of an unprotected CFS section for the same steel tube temperature, as shown in Figure 4, as the protected section will have taken a longer to reach that steel temperature compared to an unprotected section.

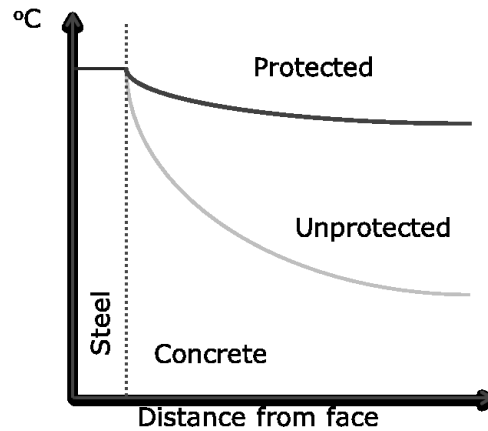


Figure 4: Schematic showing theoretical thermal profiles within unprotected and protected CFS sections.

The shallower the thermal gradient within a CFS section, the more ‘efficient’ the concrete core is at acting like steel. This means that the concrete core efficiency factor value for an unprotected CFS sections will always be smaller than for a similar protected CFS section, thus the effective section factor will be greater, and the resulting prescribed DFTs will be larger. By using the unprotected CFS sections’ concrete core efficiency factor calculations and effective section factor calculations in equations (4) and (5) to design the DFTs for protected CFS sections, the results will be conservative.

Experiments

To assess the experimental validity of using equations (4) and (5) to prescribe DFTs for protected CFS sections and thus provide less conservative interim design guidance for protected CFS section in fire, the authors conducted four tests (tests 4-7 in Table 1) on protected CFS columns exposed to the ISO-834 standard fire; three 323.9 Ø × 10 mm wall thickness sections, and one 219.1 Ø × 8 mm wall thickness section. These columns were filled with normal strength concrete that was allowed to cure for at least 28 days before testing, as recommended by Rush¹¹, to ensure that a majority of the free moisture content was chemically fixed, and to represent real, in-service columns. The columns were instrumented with eight Inconel sheathed K-Type thermocouples, as shown in Figure 1, and designed in line with available design guidance¹⁷.

The protection thickness (DFT) design method used was similar as the current UK guidance; however Equation (4) was used to determine the effective section factor rather than Equation (1), with an assumed design limiting steel temperature of 520°C. The required fire resistance time was varied for the three 323.9 Ø x 10 mm sections as 60, 90, and 120 minutes, respectively, whilst the 219.1 Ø x 8 mm wall thickness specimen was designed for a required fire resistance time of 90 minutes. The authors found that, using Equation (4), the resulting effective section factors were lower than the minimum section factors available for the specific intumescent product used, namely InterChar 1120 in this case (note: the specific product name is used only for the purposes of factual accuracy). Therefore the applied thickness was the minimum thickness defined by the available tabulated data for use of this product on unfilled sections, which is 25 mm. Table 1 shows the calculated and designed section factors (*New* and *Des.*, respectively) for the new column tests and the applied DFTs for each of the columns. Table 1 also shows three similar test results taken from Rush et al.⁸, where the section factor and applied DFTs were designed using Equation (1) (*Ed.*). The reduction in the section factor reduces the required applied DFT to the section, which in these experiments result in a

0.2mm DFT reduction between specimens No. 1 and 5. This can lead to a large savings on both material and labour costs, as the number of coats of the intumescent product may be reduced, when applied to a whole building rather than on a single element.

Table 1: Selected temperature results and specimen details, including effective section factors and applied dry film thicknesses, for the tests specimens and selected similar specimens presented by Rush¹¹

| | Test No. | Diameter | Wall thick. | F.R. (=t _{FURN}) | H _p /A _{eff} (m ⁻¹) | | | Appl. DFT | Steel | | |
|--------------------|----------|-----------|-------------|----------------------------|---|-------|-------|-----------|-------------|---------|---------------|
| | | Ø (mm) | (wt) (mm) | (mins) | Ed. | New | Des. | (mm) | Temp @ (°C) | | Mins to 520°C |
| | | | | | | | | | 90 min | 120 min | |
| Rush ¹¹ | 1 | 323.9 (a) | 10 | 90 | 40.30 | N/A | 40.30 | 3.50 | 204.0 | 244.0 | - |
| | 2 | 323.9 (b) | 10 | 90 | 40.30 | | 40.30 | 3.60 | 206.0 | 246.0 | - |
| | 3 | 219.1 | 8 | 90 | 45.03 | | 45.03 | 3.50 | 204.0 | 274.0 | - |
| New | 4 | 323.9 | 10 | 60 | 45.10 | 24.56 | 25.00 | 1.28 | 490.6 | - | 97 |
| | 5 | 323.9 | 10 | 90 | 40.30 | 17.78 | 25.00 | 3.32 | 235.8 | 302.3 | 194 |
| | 6 | 323.9 | 10 | 120 | 37.05 | 13.94 | 25.00 | 4.06 | 226.7 | 281.3 | 201 |
| | 7 | 219.1 | 8 | 90 | 45.03 | 21.97 | 25.00 | 3.32 | 257.5 | 341.8 | 175 |

Table 1 shows the steel tube temperatures at 90 and 120 minutes for all the tests, and for the *New* tests the time to reach the designed steel limiting temperature of 520°C whilst Figure 5 shows the average observed steel temperatures for all seven of the tests presented in Table 1. Both Table 1 and Figure 5 show that when using the new method for calculating the effective section factor (i.e. Equation (4)), the limiting temperatures are not reached until more than 30 minutes after the designed fire resistance times for tests No. 4-7, and in some cases more than double to F.R. time (e.g. Test 5).

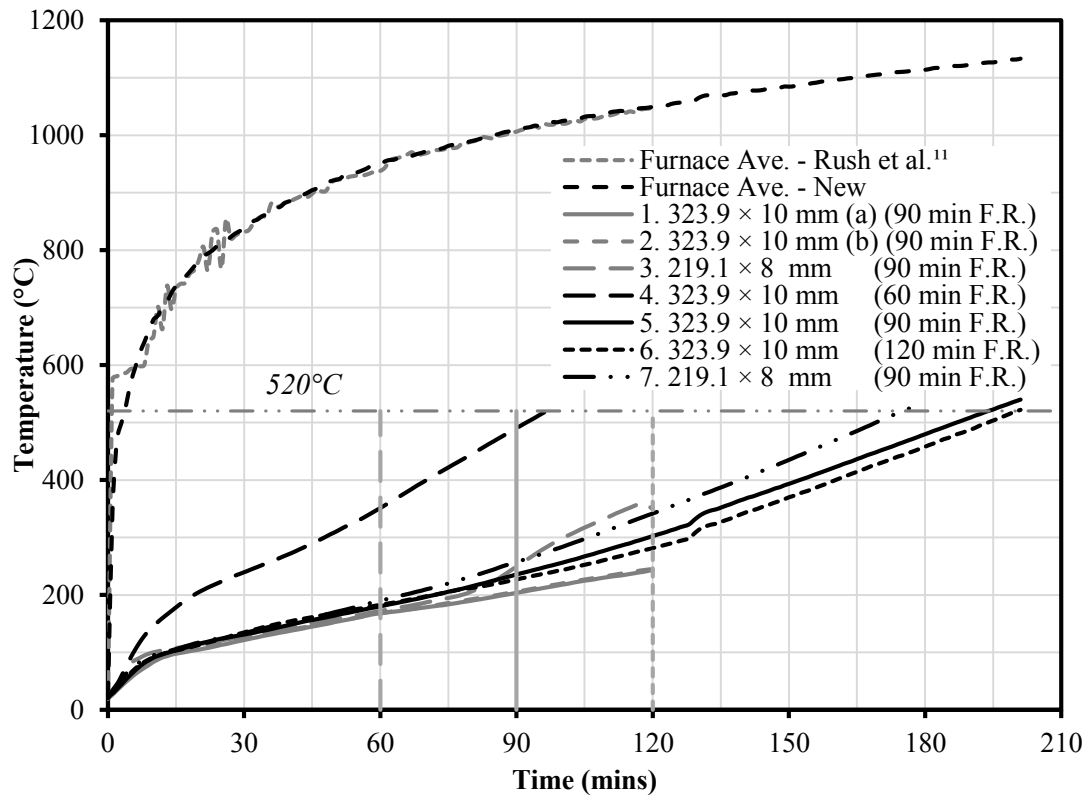


Figure 5: Observed steel tube and furnace temperatures from all 7 protected tests detailed in Table 1.

The conservatism seen in both Table 1 and Figure 5 was, as expected, due to the use of unprotected effective section factors from equations (4) and (5). Whilst this approach is not necessarily scientifically based, it has been shown experimentally to be conservative to such a degree that it is reasonable to assume the new proposed design method is safe and valid for this particular intumescent product. It should be noted that the tests 1-3 were conducted in a floor furnace, whereas tests 4-7 were conducted in a small cube furnace. The smaller furnace is known to result in a larger heat flux to the specimens for the same gas phase temperatures, due to many factors including size, shape, lining type, fuel used, and the size of the specimens being tested¹¹. This means that tests 4-7 were, in reality, exposed to a higher incident heat flux than those tests previously presented⁸, and yet the new method still provides conservative results.

The conclusion resulting from the tests on four specimens designed with the new method is that if the effective section factor calculated using equations (4) and (5) is lower than the minimum tabulated product specific section factor determined by the manufacturer, then the minimum section factor DFT should be applied, providing that this results, as in the cases presented herein, in conservative observed times to limiting temperatures as validated by furnace testing. This means that for the product presented herein, if equations (4) and (5) result in effective section factors below 25m^{-1} , which was the case for all the specimens tested, then the minimum DFT should be applied.

CONCLUSIONS

This paper has presented selected results from standard furnace tests on protected CFS sections with intumescent fire protection. Based on analysis of the test data and comparison against available design guidance, a number of conclusions can be drawn.

The current method of prescribing intumescent coating DFTs for CFS sections is overly conservative and thus inefficient. The design limiting steel temperatures were generally not reached during testing of samples designed according to available guidance presented by Rush et al.⁸ with recorded steel tube temperatures of 14 protected CFS sections some 250°C less than the designed limiting temperature of 520°C at the required fire resistance time.

An improved and more physically realistic instantaneous effective section factor model for unprotected CFS sections has been proposed, incorporating the effects of the size of the section and the required fire resistance time; this was developed⁸ using equivalent methods as the currently available UK fire design guidance for CFS sections. The new method was used to calculate the effective section factor for four protected CFS sections, resulting in section factor values below the minimum section factors available for specifying DTFs of the product used herein, i.e. 25m^{-1} .

By applying the minimum design DFT corresponding to the minimum section factor for which data were available for this product, it was shown experimentally that this new method can be safely and conservatively used in the prescription of the specific intumescent protection product across all realistic fire resistance periods (i.e. greater than 60 mins) for CFS sections.

Whilst the new method considerably simplifies the design of the specific intumescent products tested to a single section factor, it remains conservative, with all tested specimens not reaching the limiting steel tube temperature of 520°C more than 30 minutes after the design F.R., and in some instances more than 100 minutes after the designed F.R.. Additional research would help to understand intumescent protection on CFS sections and, if necessary, to develop a more scientifically-based method for their prescription.

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